ASETSDefense 09

Cadmium Coating Alternatives for High-Strength Steel JTP – Phase II

Westminster, CO
3 September 2009

Air Force Technical Point of Contact: Dr. Elizabeth Berman
***CTC* Subtask Manager: Clayton Drees**

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **03 SEP 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Cadmium Coating Alternatives for High- Strength Steel JTP - Phase II**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,Wright Patterson AFB,OH,45433**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
ASETSDefense 2009: Sustainable Surface Engineering for Aerospace and Defense Workshop, August 31 - September 3, 2009, Westminster, CO. Sponsored by SERDP/ESTCP.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**42**	

Project Overview

Objective

- Assess DoD-selected Cadmium alternatives in accordance with the DoD-approved Joint Test Protocol (JTP) for both traditional plating and brush plating of HSS applications.
  (JTP is available at www.jgpp.com)

Approach

- Two-phased approach:
  - Phase I (HE and adhesion testing): NAVAIR (complete)
  - Phase II (JTP test matrix): AFRL/*CTC* (complete)
- Down-selection of candidates after each phase of testing is complete (Phases I & II)

Project Team Members

- **AFRL – Dr. Elizabeth Berman**
- ***CTC*** **– Mr. Clayton Drees, Ms. Leanne Debias**
- **NAVAIR – Mr. Steve Brown**
- **Boeing – Mr. Joe Osborne**
- **ARL – Mr. Brian Placzankis**
- **WMTR – Mr. Jay Curry**
- **Hill AFB – Mr. Nate Hughes**
- **Alumiplate – Mr. Gus Vallejo**
- **Marshall Labs – Mr. John Marshall**

Phase I Overview and Selection Process

- **Alternatives Tested in Phase I**
  - Primary coatings:
    - ✓ Sputtered Aluminum (Marshall Labs)
    - ✓ Electroplated Aluminum (Alumiplate)
    - ✓ LHE Zn-Ni (Dipsol IZ-C17)
    - Acidic Zn-Ni (Boeing, Seattle)
    - Sn-Zn (Dipsol)
  - Repair coatings:
    - ✓ Brush Zn-Ni (SIFCO 4018)
    - ✓ Brush Sn-Zn (LDC 5030)
    - ✓ Spray Aluminum-ceramic (Sermetel 249/273)

- **Tests Conducted in Phase I**

  -Hydrogen Embrittlement

  -Re-embrittlement

  -Adhesion

- **Selection Process**

  -WebEx Teleconference to review results

  -E-mail voting to determine Phase II candidates

  ✓ = Down-selected coating for Phase II

Phase II Tests

Test Category	Test	Testing Facility
General Properties	Appearance	*CTC* (POC – Leanne Debias)
	Throwing power and alloy composition uniformity	*CTC*
	Stripability	NAVAIR (POC – Steve Brown)
	Galvanic potential	Not Conducted
Adhesion	Bend adhesion	NAVAIR
	Paint adhesion	NAVAIR
Corrosion	Unscribed NSS* (bare)	ARL (POC – Brian Placzankis)
	Scribed NSS* (bare)	ARL
	Galvanic corrosion resistance	ARL
	Fluid corrosion resistance	ARL
	Scribed, painted salt spray	NAVAIR (paint), ARL (test)
	Scribed and unscribed SO_2 salt spray	NAVAIR
Lubricity	Run-on/Break-away torque	WMTR (POC – Jay Curry)
	Torque-tension & torque-tension of corrosion-exposed fasteners	WMTR
Reparability	Appearance & Thickness	*CTC*
	Bend adhesion	ARL
	Paint adhesion	ARL
	Scribed and unscribed salt spray	ARL
Quality Assurance	Hydrogen embrittlement – notched bar	NAVAIR

Primary Coating Appearance Test Results

Coating	Appearance Results
LHE Cadmium (Baseline) – Hill AFB	Coating is continuous but not uniform, showing some edge effect; coating is smooth, adherent, and free from blisters, pits, excessive powder, and contamination
IVD Aluminum (Baseline) – Hill AFB	Coating is continuous, uniform, smooth, adherent, and free from blisters, pits, excessive powder, and contamination
IVD Aluminum (Baseline) – Cametoid Technologies	Coating is continuous, uniform, smooth, adherent, and free from blisters, pits, excessive powder, and contamination
LHE Zinc-Nickel (Dipsol IZ-C17)	Coating is continuous but not uniform also containing a few spots of possible contamination; otherwise, the coating is smooth, adherent, and free from pits, blisters, and excessive powder
Electroplated Aluminum	Coating is continuous, uniform, smooth, adherent, and free from blisters, pits, excessive powder, and contamination
Sputtered Aluminum	Coating is continuous, uniform, smooth, adherent, and free from blisters, pits, excessive powder, and contamination

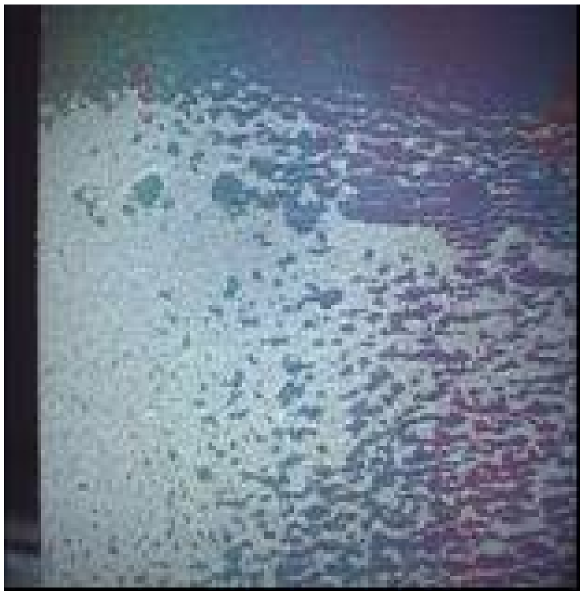
All Primary Coatings Passed Appearance Testing

Primary Coating Bend Adhesion Test Results

Coating	Bend Adhesion Results		
	4130 steel substrate	17-4 PH stainless substrate	Ti-6-4 substrate
LHE Cadmium (Baseline) – Hill AFB	Not required	Pass	Pass
IVD Aluminum (Baseline) – Hill AFB	Not required	Not required	Not required
LHE Zinc-Nickel	Pass – cracking of coating up to 3/8”	Pass – no cracking or defect	Fail – during 1st bend cycle; spalling beyond 3/8”
Electroplated Aluminum	Pass	Pass - no cracking or defect	Fail – edge buckling to ½”
Sputtered Aluminum	Pass- no cracking or defect	Pass - no cracking or defect	Pass - no cracking or defect

- **Mixed Bend Adhesion Results**
  - **All primary coatings passed using both 4130 steel & 17-4 stainless**
  - **LHE Zinc-Ni and electroplated Al failed bend adhesion for Ti-6-4 due to spalling and edge buckling respectively**

Primary Coating
Bend Adhesion Test Results



Zinc-Nickel on Ti-6-4

Electroplated Aluminum on Ti-6-4

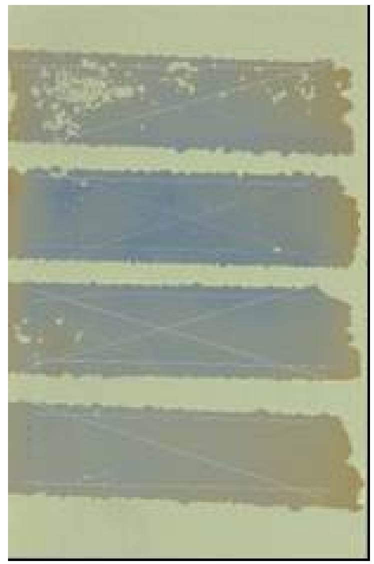
Primary Coating
Paint Adhesion Results

Coating	Paint Adhesion (1, 4, 7 day duration)		
	MIL-PRF-23377, Class C2	MIL-PRF-85582, Class C1	MIL-PRF-85582, Class N
LHE Cadmium (Baseline) – Hill AFB	Pass all durations	Pass all durations	Pass all durations
IVD Aluminum (Baseline) – Hill AFB	Pass all durations	Pass all durations	Pass all durations
IVD Aluminum (Baseline) – Commercial Vendor	N/A	N/A	N/A
LHE Zinc-Nickel	Pass all durations	Fail 4 & 7 day duration	Pass all durations
Electroplated Aluminum	Pass all durations	Pass all durations	Pass all durations
Sputtered Aluminum	Pass all durations	Pass all durations	Pass all durations

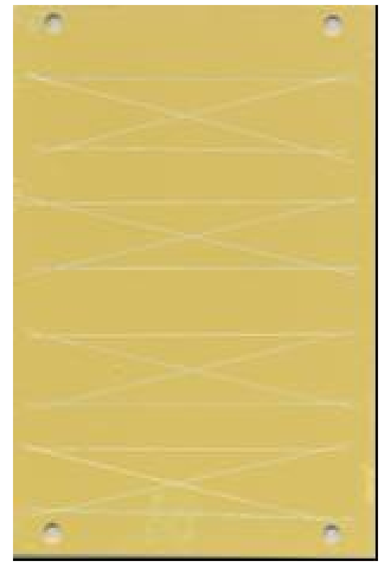
- **Primary coatings passed paint adhesion testing with one exception (LHE Zinc-Ni failed for 85582 Class C1 after 4 and 7 days)**

Primary Coating
Paint Adhesion Results

IVD Al with MIL-PRF-85582 C1, after 4 days



LHE Zn-Ni with MIL-PRF-85582 C1, after 4 days



Electroplated Al with MIL-PRF-23377, after 7 days

Sputtered Al with MIL-PRF-23377, after 4 days

Primary Coating
Neutral Salt Spray Corrosion Results

Coating	Neutral Salt Spray Corrosion Resistance	
	Unscribed Panels (maximum exposure 3000 hours)	Scribed Panels (maximum exposure 3000 hours)
LHE Cadmium (Baseline) – Hill AFB	Pass no damage – rating of 9 at termination	Pass no damage – rating of 9 at termination
IVD Aluminum (Baseline) – Hill AFB	Fail excessive rusting – rating of 0 at termination	Fail excessive rusting – rating of 0 at termination
LHE Zinc-Nickel	Pass sacrificial coating breakdown only - rating of 9 at termination	Pass sacrificial coating breakdown only - rating of 9 at termination
Electroplated Aluminum	Fail - marginal chromate depletion and pin hole formation – rating of 7 at termination	Fail sacrificial coating breakdown and rust – rating of 0 at termination
Sputtered Aluminum	Fail excessive rusting – rating of 0 at termination	Fail excessive rusting – rating of 0 at termination

- **Only LHE Zinc-Nickel performed as well as the Cd baseline in neutral salt spray corrosion resistance**

Primary Coating Galvanic Corrosion Resistance

Galvanic Corrosion Resistance Average Change in Conductivity (milliohms)									
Coating	Block Substrate	4130 Washer		17-4PH Washer		CuBe Washer		AlNiBr Washer	
		Salt Spray	Cyclic	Salt Spray	Cyclic	Salt Spray	Cyclic	Salt Spray	Cyclic
No coating	2024 Al	88.0	N/A	52.7	2.6	31.3	0	0	0
	7075 Al	68.3	N/A	270.0	N/A	12.6	0	3.9	0
LHE Cadmium (Baseline)	2024 Al	0	0	0.43	0.37	0	0	0	0.47
	7075 Al	0	0	0.27	0.47	0	0	0	0
IVD Aluminum (Baseline)	2024 Al	0	0	0.03	0	0	0	0	0
	7075 Al	0	0	0	0	0	0	0	0
LHE Zinc-Nickel	2024 Al	0.33	0	0.47	0	2.1	0	0.2	0
	7075 Al	0.47	0.03	0.60	0	3.2	0	0.73	0
Electroplated Aluminum	2024 Al	0.17	0	0	0	0	0	0.47	0
	7075 Al	1.53	0	0.60	0	0	0	0.73	0
Sputtered Aluminum	2024 Al	0.1	0	0.07	0	0.07	0	0.07	0
	7075 Al	0	0	0	0	0.17	0.03	0.33	0

Red = Worse than Cd
Blue = Equal to or better than Cd
Green = Marginally worse than Cd

- Sputtered Al performed best, followed by electroplated Al and LHE Zn-Ni

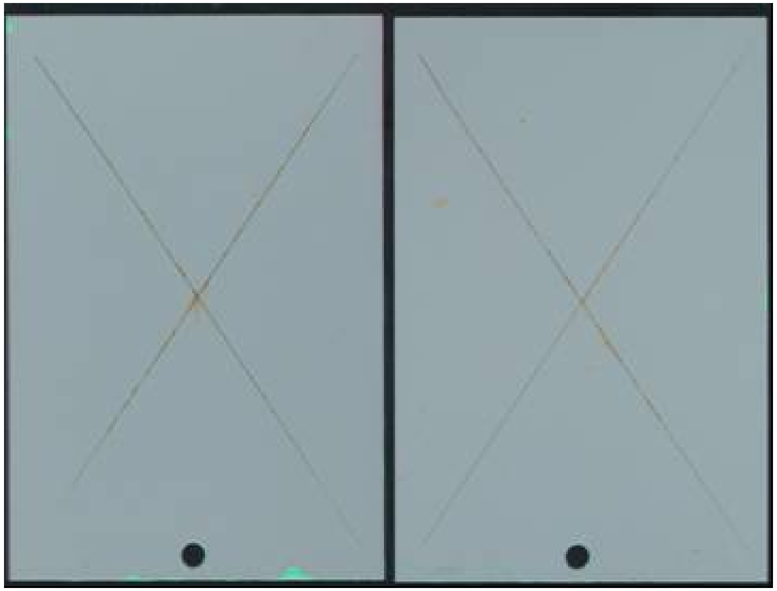
Primary Coating Fluid Corrosion Resistance Results

- Cadmium baseline, IVD Al baseline, and LHE Zinc-Nickel performed similarly, with measurable weight changes and appearance changes for exposure to paint removers
- Electroplated Al performed better than cadmium and IVD Al for all fluids tested
- Sputtered Al performed worst, with weight changes noted for one paint remover, aircraft deicer, reagent water, and water-saturated lubricant

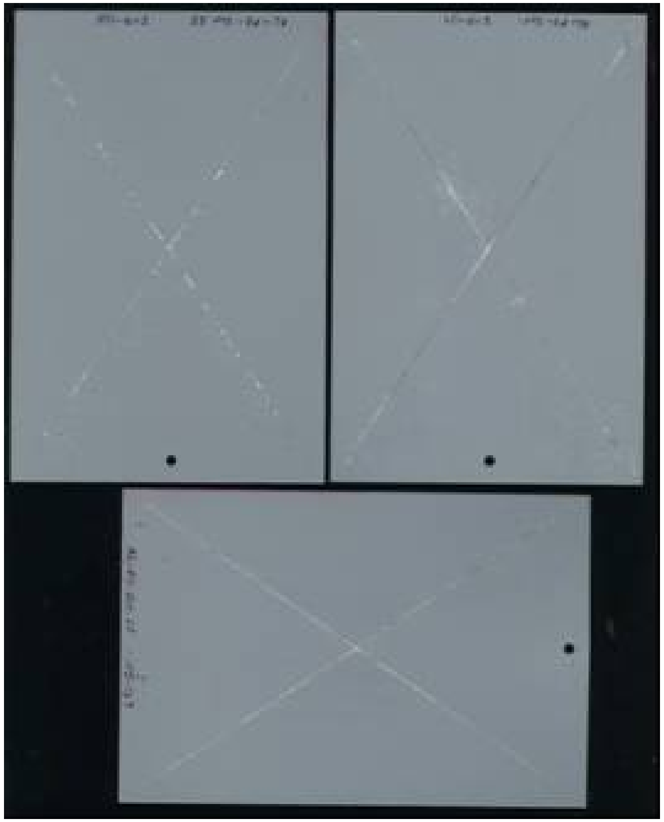
Primary Coating
Scribed, Painted Salt Spray Results

- Three primers tested for a maximum exposure of 3000 hours
- Cadmium performed the best with all 9 ratings after 3000 hours
- LHE Zn-Ni performed similarly to cadmium, with three panels achieving 9 ratings, though two others achieved a 4 and 5 for creepage and pinhole rust
- Electroplated Al lasted 3000 hours but received ratings ranging from 0 – 5
- Sputtered Al and IVD Al both failed to achieve 3000 hours of exposure due to excessive rust

Representative Images of Scribed, Painted Salt Spray Panels

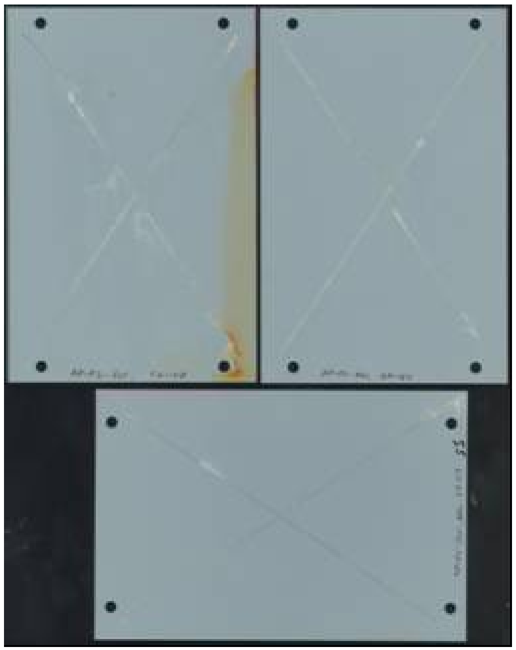


Cd-plated panels
(3000 hours)

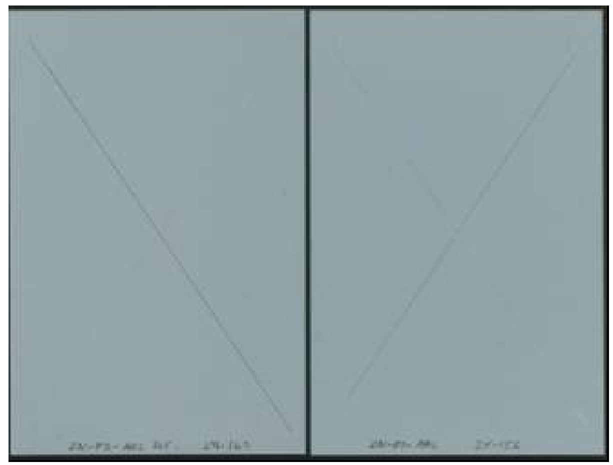


IVD Al Coated Panels
(2000 hours)

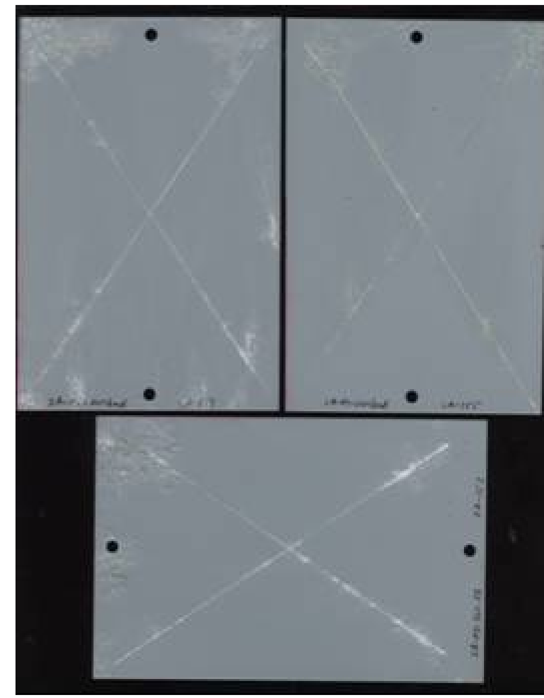
Representative Images of Scribed, Painted Salt Spray Panels



Electroplated Al
Panels
(3000 hours)



LHE Zn-Ni Panels
(2000 hours)



Sputtered Al
Panels
(1500 hours)

Primary Coating Run-on/Breakaway Torque Test Results

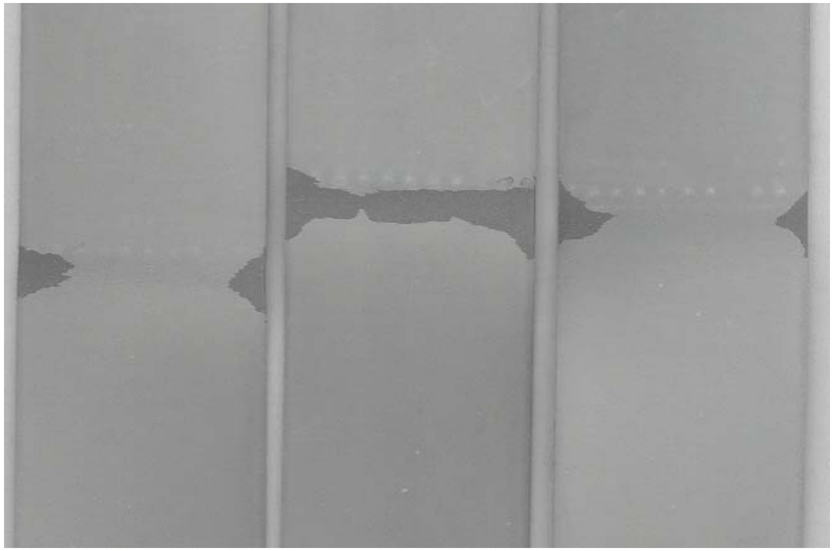
- Reporting Maximum Locking Torque and Breakaway Torque for the 3/8-inch and 5/8-inch fasteners
- 3/8-inch LHE Zinc-Nickel, electroplated aluminum and sputtered aluminum fasteners pass JTP criteria (9.5 in-lbs)
- 5/8-inch Cadmium baseline and all coatings fail JTP criteria (32 in-lbs)

Repair Coating
Appearance and Thickness Results

Coating	Appearance Results	Average Thickness (0.3 – 0.6 mils requested)
Brush Plated Cadmium (Baseline) – OEM	Coating is continuous but not uniform, showing swirls from processing; coating is smooth, adherent, and free from blisters, pits, excessive powder, and contamination	1.34 mils +/- 0.20
Brush Plated Zinc-Nickel – OEM	Coating is not continuous or uniform; coating is adherent, but rough, with excessive powder and possible rust spots	0.89 mils +/- 0.17
Brush Plated Tin-Zinc – OEM	Coating is continuous but not uniform, with a dark brown area through the center of the panel; the coating is smooth and adherent, but has excessive powder	0.5 mils +/- 0.06
Sprayed Al - ceramic – OEM	Coating is continuous and uniform, smooth, adherent, and free from pits, blisters, excessive powder, and contamination	1.42 mils +/- 0.09

Repair Coating
Bend Adhesion Test Results

Brush Plated Cd (baseline)



Sprayed Aluminum - ceramic

- Brush plated Cd and sprayed Aluminum-ceramic exhibit significant adhesion losses during bend testing
- Brush plated Sn-Zn and Zn-Ni passed adhesion testing
- Results consistent with those observed during Phase I testing

Repair Coating
Neutral Salt Spray Corrosion Results

U.S. AIR FORCE

Coating	Neutral Salt Spray Corrosion Resistance	
	Unscribed Panels (maximum exposure 3000 hours)	Scribed Panels (maximum exposure 3000 hours)
Brush LHE Cadmium (Baseline) – Boeing, St. Louis	Pass no damage – rating of 10 at termination	Pass no damage – rating of 9 at termination
Brush Tin-Zinc – Boeing, St. Louis	Fail excessive rusting – termination at 1000 hours	Fail severe rusting – termination at 500 hours
Brush Zinc-Nickel – Boeing, St. Louis	Pass sacrificial coating breakdown only - rating of 9 at termination	Pass sacrificial coating breakdown – average rating of 7.7 at termination
Sermetel 249/273 – Boeing, St. Louis	Fail excessive rusting – termination at 500 hours	Fail excessive rust – termination at 500 hours

- **Only Brush Zinc-Nickel performed as well as the Cd baseline in neutral salt spray corrosion resistance**

Summary

- **Phase II testing has been completed (*CTC*, NAVAIR, ARL, WMTR)**
- ***Mixed results* obtained for primary and repair coatings:**
  - **Primary Coatings**
    - Electroplated Al performed similar to or better than Cd in most tests
      - But failed all neutral salt spray corrosion tests and painted cyclic SO_2 salt spray tests, and exhibited inconsistencies in composition for throwing power tests
    - LHE Zn-Ni performed best in all neutral salt spray tests and in painted cyclic SO2 salt spray tests,
      - But exhibited failures in bend adhesion, paint adhesion, galvanic corrosion resistance, and hydrogen re-embrittlement
    - Overall, sputtered Al performed worst, failing the most tests,
      - But yielded the best galvanic corrosion resistance and bend adhesion results
  - **Repair coatings**
    - Brush plated Zn-Ni performed best overall, but failed appearance tests due to excessive surface roughness
    - Brush plated Sn-Zn failed corrosion tests
    - Sermetel coating failed adhesion and corrosion tests

Back-Up Slides

Description of Testing Methods

U.S. AIR FORCE

- **General properties (primary coatings)**
  - Appearance – visual exam
  - Throwing power
    - Test fixture surrounds panel, with one access slot
    - Fixture + panel is placed in solution at 3 different orientations
    - Uniformity of coating is measured at 3 locations on each panel
  - Strippability
    - Specimens are stripped by vendor-recommended method
    - Half of specimens are tested
    - Remaining specimens are recoated and tested
      - Hydrogen Embrittlement
      - Adhesion
  - Galvanic Potential
    - Three types of measurements are performed over 5 days: open circuit potential measurement, electrochemical impedance spectroscopy, and tafel analysis

Description of Testing Methods (continued)

- **Adhesion (primary coatings)**
  - Bend adhesion
    - Specimen is bent back and forth through 180° until the coating and/or substrate ruptures
  - Wet tape paint adhesion
    - Primers are applied to test panels (14 day cure)
      - MIL-PRF-85582 Type I, Class C1
      - MIL-PRF-85582, Type I, Class N
      - MIL-PRF-23377 Type 1, Class C
    - Panels are immersed in distilled water at following conditions:
      - 23°C for 24 hours
      - 49°C for 96 hours
      - 65°C for 168 hours
    - Perform tape adhesion according to ASTM D3359, Method B

Description of Testing Methods (continued)

- **Corrosion (primary coatings)**
  - Unscribed and Scribed Neutral Salt Spray (bare)
    - Bare panels exposed to a 5% NaCl solution sprayed at 35°C, until coating failure
  - Galvanic corrosion resistance
    - Components of test assemblies: 2024 or 7075 Al test block, coated with MIL-PRF-85582, Class 1, Type N, test washer (4 alloys), nuts, bolts, anodized washers
    - Test assemblies are exposed to salt fog for 168 hours and cyclic corrosion for 336 hours
  - Fluid corrosion resistance
    - Immerse panels in specified fluid at 100°F for 7 days
    - Test fluids: sea water, deicers, paint removers, cleaners, lubricants (14 total)

Description of Testing Methods (continued)

- **Corrosion (continued)**
  - Scribed Painted Neutral Salt Spray
    - Test panels are primed with
      - MIL-PRF-85582 Type I, Class C1
      - MIL-PRF-85582, Type I, Class N
      - MIL-PRF-23377 Type 1, Class C
    - Test panels are exposed to 5% NaCl solution at 35°C for 3000 hours or until red rust
  - Scribed and Unscribed SO_2 Salt Spray
    - Unpainted panels and scribed, painted panels (same primers as above)
    - Expose to 5% NaCl and SO_2 gas IAW ASTM G85 A4 until coating failure (red rust)

Description of Testing Methods (continued)

- **Lubricity (primary coatings)**
  - Run-on/Breakaway Torque
    - Record maximum locking torque after 2 complete turns from point where the top of the nut is flush with the end of the bolt
    - Breakaway torque is measured during removal of the nut
    - Measure for 15 lock/breakaway cycles and examine at 10x for thread damage
  - Torque Tension
    - Measure torque and induced load with test fixture for the range of 30%-60% of the bolt UTS
    - Repeat for a total of 5 cycles
  - Torque Tension of corrosion-exposed fasteners
    - Assemble bolts/nuts/washers onto an Al test block
    - Torque to 60% of UTS for bolt and exposed to cyclic corrosion for 28 days
    - Measure breakaway torque and compare to unexposed set

Description of Testing Methods (continued)

- **Repairability (repair brush coatings)**
  - Initial qualification – coating applied to bare substrate and tested
  - Final qualification – candidate primary coating of choice is abraded to generate a bare area and then repaired with a brush plating
  - Testing Methods
    - **Appearance** – visual exam
    - **Bend adhesion** – bend specimen back over itself until rupture
    - **Thickness** – cross-section and microscopy
    - **Scribed and unscribed salt spray (bare)** – until failure
    - **Paint adhesion** – apply primers, immerse in distilled water at same temps/times as primary coatings, and perform cross-hatch adhesion according to ASTM D3359, method B

- **Quality assurance – HE testing to compare to Phase I**

Alternative Selection – Phase I

Down-selected Coatings for Phase II:

- Primary test coatings
  - LHE Zinc-Nickel (Dipsol IZ-C17)
  - Electroplated Aluminum
  - Sputtered Aluminum
  - Controls:
    - Cadmium
    - IVD Al: Hill AFB flat panels
    - IVD Al: Cametoid fasteners, washers and HE bars
- Repair test coatings (Cd brush control)
  - Aluminum-Ceramic Repair Coating (Sermetel)
  - Zinc-Nickel brush repair
  - Tin-Zinc brush repair
  - Control – Cd brush

All Phase II testing methods were performed according to the procedures and requirements in the JTP.

Primary Coating Stripability Test Results

Coating	Change in Hydrogen Embrittlement	Change in Bend Adhesion
LHE Cadmium (Baseline) – Hill AFB	Not required	Not required
IVD Aluminum (Baseline) – Hill AFB	Not required	Not required
IVD Aluminum (Baseline) – Commercial Vendor	Not required	Not required
LHE Zinc-Nickel	Pass – average of 88.5% fracture strength for 200 hours (3 of 4 specimens)	Fail – coating failure in 1-2 bend cycles
Electroplated Aluminum	Pass – average of 93.6% fracture strength for 200 hours (4 of 4 specimens)	Pass – no coating failure before substrate rupture (12 cycles)
Sputtered Aluminum	Samples not returned	Samples not returned

***Mixed stripability results*:**

•Electroplated Al passed

•LHE Zinc-Ni failed due to change in bend adhesion in 1-2 bend cycles

Throwing Power Fixture

- Test coupon is inserted in fixture and entire assembly is submerged in plating solution
- Fixture alignment can be varied to simulate multiple complex geometries
- Composition readings taken every 0.5” down the length of the coupon

LHE Zinc-Nickel
Throwing Power Composition Results

U.S. AIR FORCE

Reading #	Wt % Oxygen	Wt% Iron	Wt% Nickel	Wt% Zinc
1	1.6%	0.3%	15.9%	82.2%
2	1.5%	0.3%	16.1%	82.1%
3	1.9%	0.5%	15.7%	81.9%
4	1.9%	1.5%	15.6%	81.0%
5	2.1%	1.7%	15.3%	80.8%
6	1.9%	2.0%	14.1%	82.0%
7	2.0%	2.8%	14.3%	80.8%
8	2.0%	2.8%	14.0%	81.2%
9	1.5%	3.2%	13.6%	81.7%

Panel #1: notch in fixture facing upward with open end of fixture facing the node

Reading #	Wt % Oxygen	Wt% Iron	Wt% Nickel	Wt% Zinc
1	1.4%	0.2%	15.9%	82.5%
2	1.7%	0.3%	15.9%	82.1%
3	1.8%	0.3%	15.2%	82.7%
4	1.8%	0.8%	15.4%	82.1%
5	1.7%	1.0%	15.8%	81.6%
6	1.8%	1.3%	14.7%	82.1%
7	1.4%	1.5%	14.9%	82.2%
8	1.7%	1.7%	14.5%	82.1%
9	2.2%	2.2%	14.0%	81.6%

Panel #2: notch in fixture facing upward with open end of fixture facing away from the node

Reading #	Wt % Oxygen	Wt% Iron	Wt% Nickel	Wt% Zinc
1	1.7%	5.6%	11.2%	81.6%
2	2.0%	2.6%	11.9%	83.5%
3	2.2%	1.8%	13.3%	82.7%
4	2.4%	1.5%	14.3%	81.9%
5	2.2%	1.2%	15.1%	81.5%
6	2.3%	0.8%	15.4%	81.5%
7	2.1%	0.8%	15.0%	82.1%
8	2.4%	0.8%	15.2%	81.6%
9	2.6%	1.4%	15.5%	80.5%

Panel #3: notch in fixture in vertical position

- Nickel and Iron compositions vary along panel length (trend depends on fixture geometry)
- Oxygen and Zinc compositions are more consistent
- Fixture geometry for Panel #3 resulted in most significant composition variation

Electroplated Aluminum Throwing Power Composition Results

U.S. AIR FORCE

Reading #	Wt % Oxygen	Wt% Aluminum	Wt% Chromium	Wt% Iron	Wt% Nickel
1	11.8%	77.6%	5.2%	2.5%	3.0%
2	10.8%	78.7%	4.7%	2.4%	3.5%
3	10.6%	74.9%	4.8%	2.9%	6.8%
4	9.1%	72.5%	4.4%	3.2%	10.8%
5	11.7%	74.9%	5.0%	3.2%	5.2%
6	12.3%	76.8%	5.2%	3.0%	2.9%
7	12.0%	76.6%	5.6%	3.2%	2.6%
8	11.8%	76.6%	5.7%	3.0%	2.9%
9	10.8%	77.4%	4.3%	3.0%	4.5%

Panel #1: notch in fixture in vertical position

Reading #	Wt % Oxygen	Wt% Aluminum	Wt% Chromium	Wt% Iron	Wt% Nickel
1	13.3%	76.9%	4.7%	2.6%	2.5%
2	11.5%	78.7%	4.4%	2.7%	2.6%
3	10.2%	80.0%	3.7%	2.8%	3.3%
4	9.0%	79.8%	3.8%	3.2%	4.2%
5	8.7%	81.8%	3.1%	3.3%	3.2%
6	11.1%	80.0%	3.8%	3.1%	2.0%
7	9.3%	80.4%	3.9%	3.0%	3.5%
8	10.1%	78.8%	3.9%	2.8%	4.4%
9	10.8%	77.2%	2.9%	2.8%	6.3%

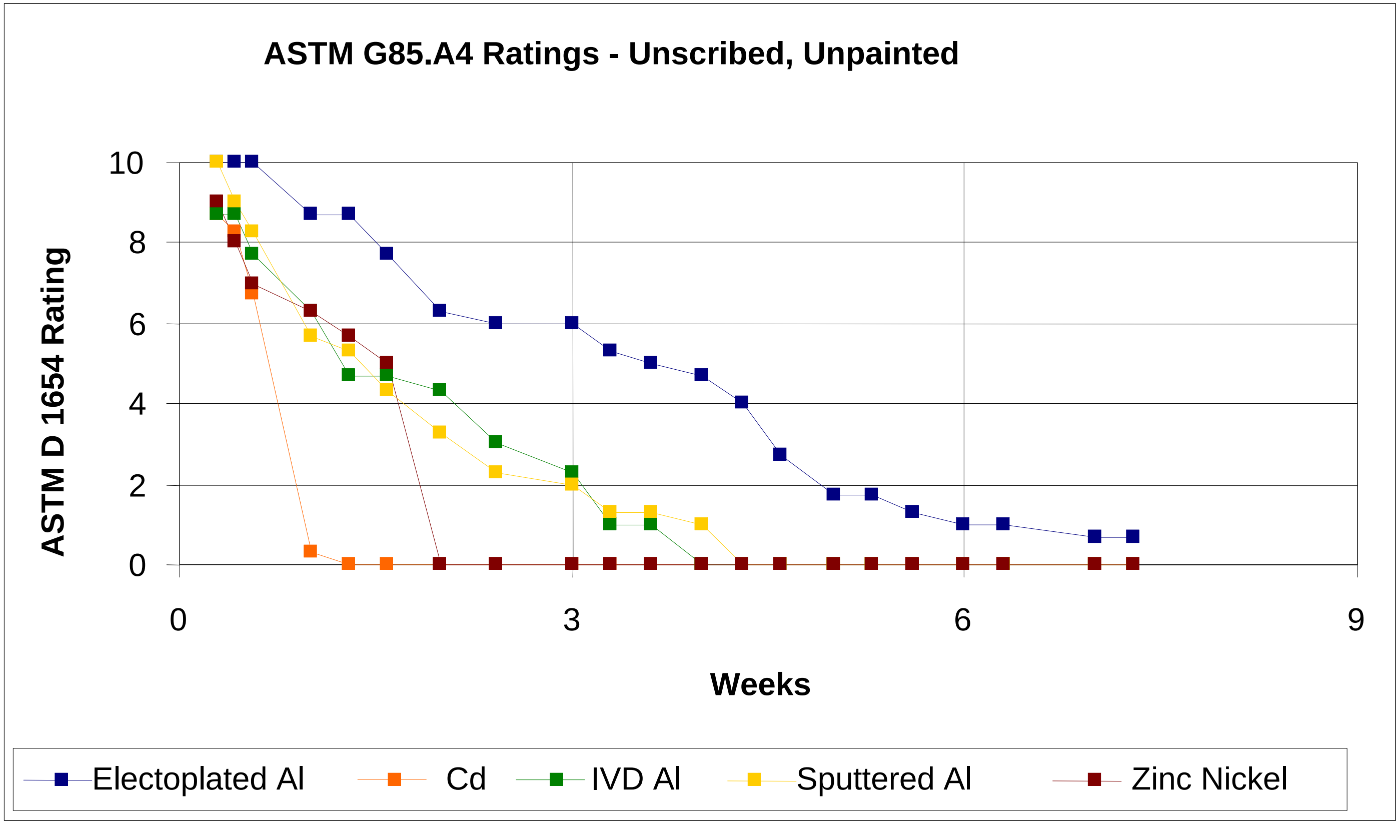
Panel #2: notch in fixture facing downward when placed in bath

Reading #	Wt % Oxygen	Wt% Aluminum	Wt% Chromium	Wt% Iron	Wt% Nickel
1	9.9%	80.5%	3.9%	3.0%	2.7%
2	11.0%	79.8%	3.9%	2.9%	2.4%
3	9.4%	79.7%	3.5%	2.7%	4.8%
4	8.2%	76.8%	2.8%	3.0%	9.2%
5	8.5%	74.6%	3.5%	3.8%	9.7%
6	8.3%	78.6%	3.0%	4.4%	5.7%
7	9.4%	77.3%	3.2%	3.2%	6.9%
8	7.9%	70.9%	2.7%	5.8%	12.7%
9	3.6%	54.4%	0.9%	4.1%	37.0%

Panel #3: notch in fixture facing upward when placed in bath

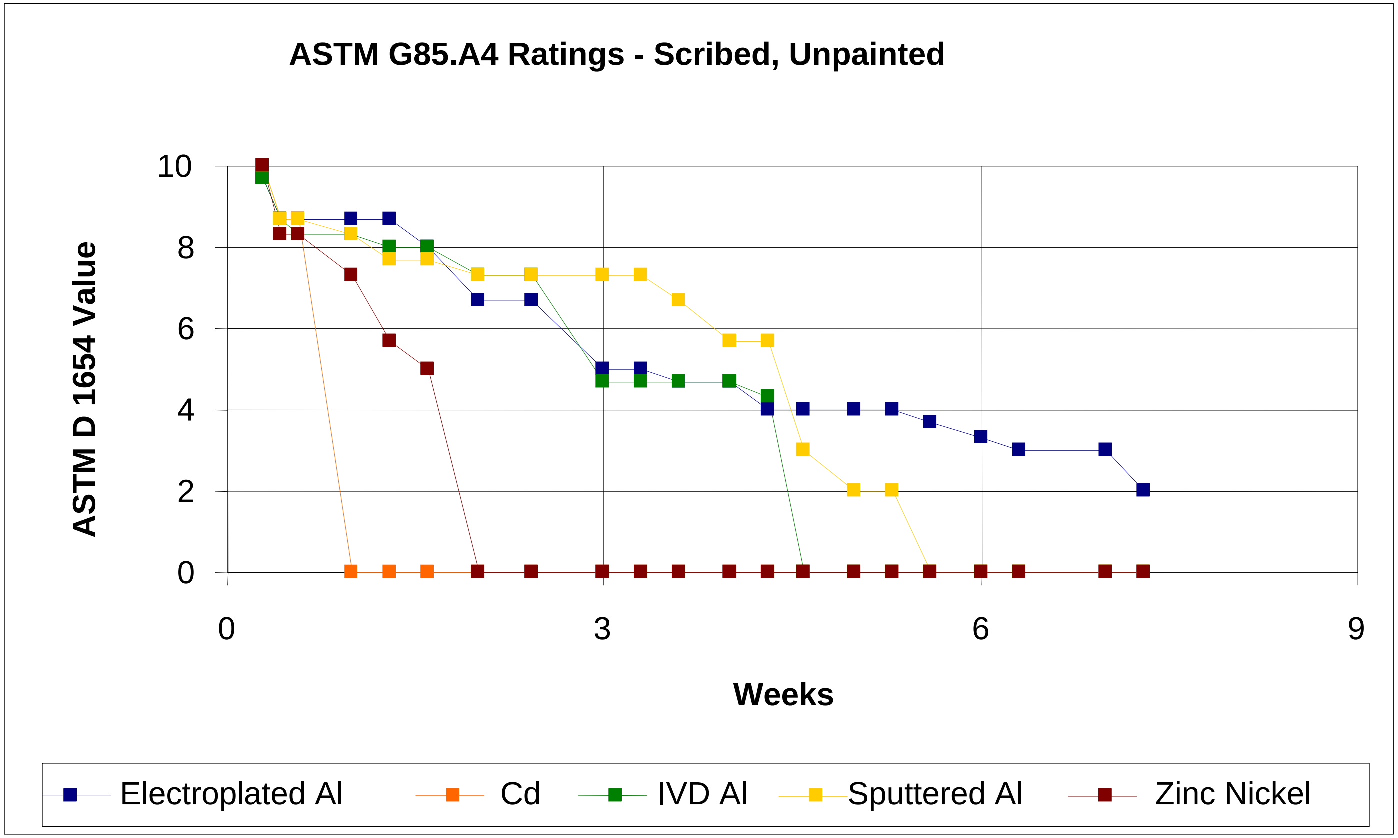
- Oxygen, Aluminum, and Nickel compositions varied considerably for each panel
- No apparent trends in data
- Final readings for Panel #3 represent significant deviations in coating composition

Primary Coating
SO_2 Salt Fog Corrosion Resistance
Unscribed, Unpainted Specimens



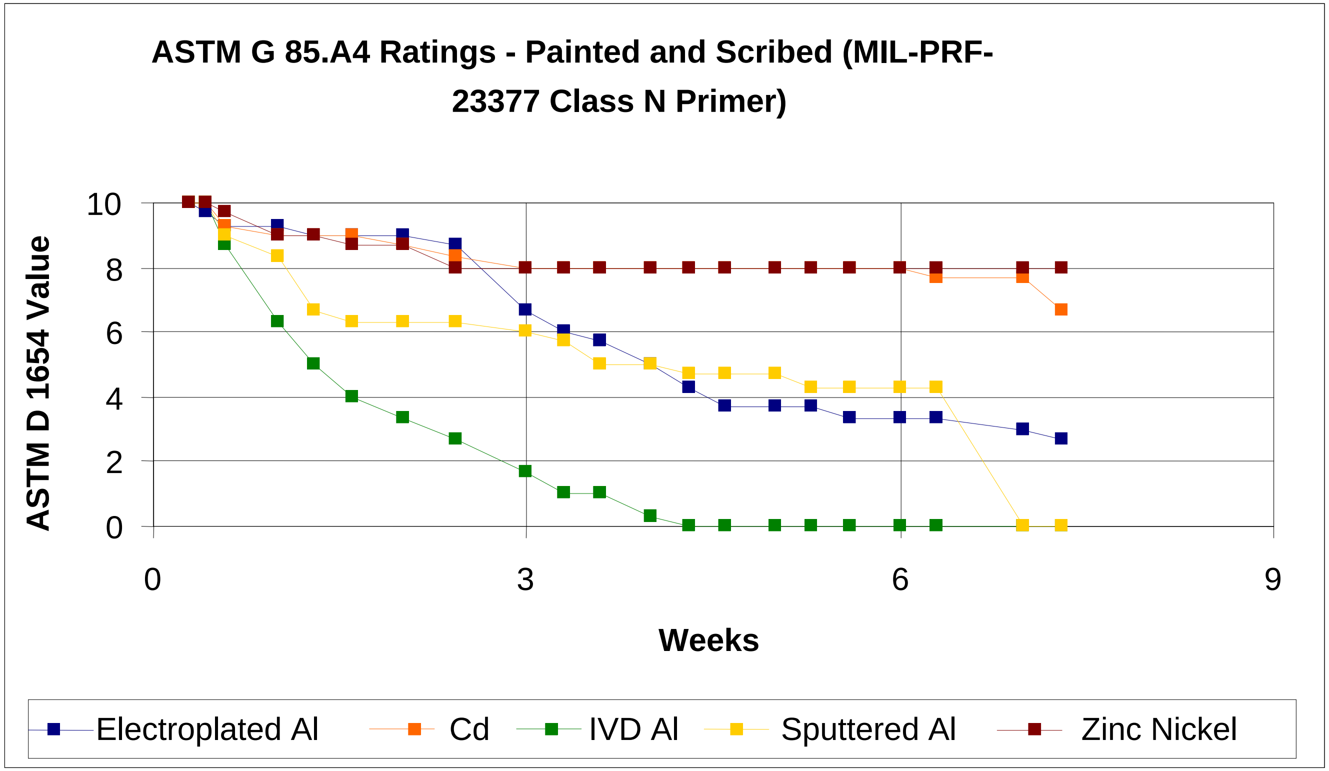
- All primary coatings outperformed baseline Cd
- Aluminum coatings yielded the best results, with electroplated aluminum showing the highest level of corrosion resistance

Primary Coating
SO_2 Salt Fog Corrosion Resistance
Scribed, Unpainted Specimens



- All primary coatings outperformed Cd in scribed testing
- Zinc-Nickel coating was significantly less effective than the aluminum coatings

Primary Coating
SO_2 Salt Fog Corrosion Resistance
Scribed, Painted Specimens



- Zinc-Nickel coating performed as well as Cd baseline when painted with MIL-PRF-23377 Class N non-chromated primer
- Aluminum based coatings were less effective, with IVD Al baseline displaying the poorest results
- Results were similar for MIL-PRF-23377 Class C2 chromated primer and MIL-PRF-85582 Class N non-chromated primer

Primary Coating
Hydrogen Re-Embrittlement Test Results

Coating	Test Fluid	Average Fracture Strength (%)	Average Time to Failure	Pass/Fail rating
Sputtered Aluminum	ASTM D 1141 Synthetic Sea Water	45.2%	0.3 hours	Fail
	3:1 Propylene Glycol	85.3%	157.6 hours	Pass
	ASTM D 1193 Ty. 2, 1M-ohm Reagent Water	48.9%	106.7 hours	Fail
Electroplated Aluminum	ASTM D 1141 Synthetic Sea Water	99.0%	160 hours	Pass
	3:1 Propylene Glycol	95.8%	159.5 hours	Pass
	ASTM D 1193 Ty. 2, 1M-ohm Reagent Water	95.7%	158 hours	Pass
LHE Zinc-Nickel	ASTM D 1141 Synthetic Sea Water	57.7%	81 hours	Fail
	ASTM D 1193 Ty. 2, 1M-ohm Reagent Water	93.0%	158.5 hours	Pass

- Only electroplated aluminum passed all conditions

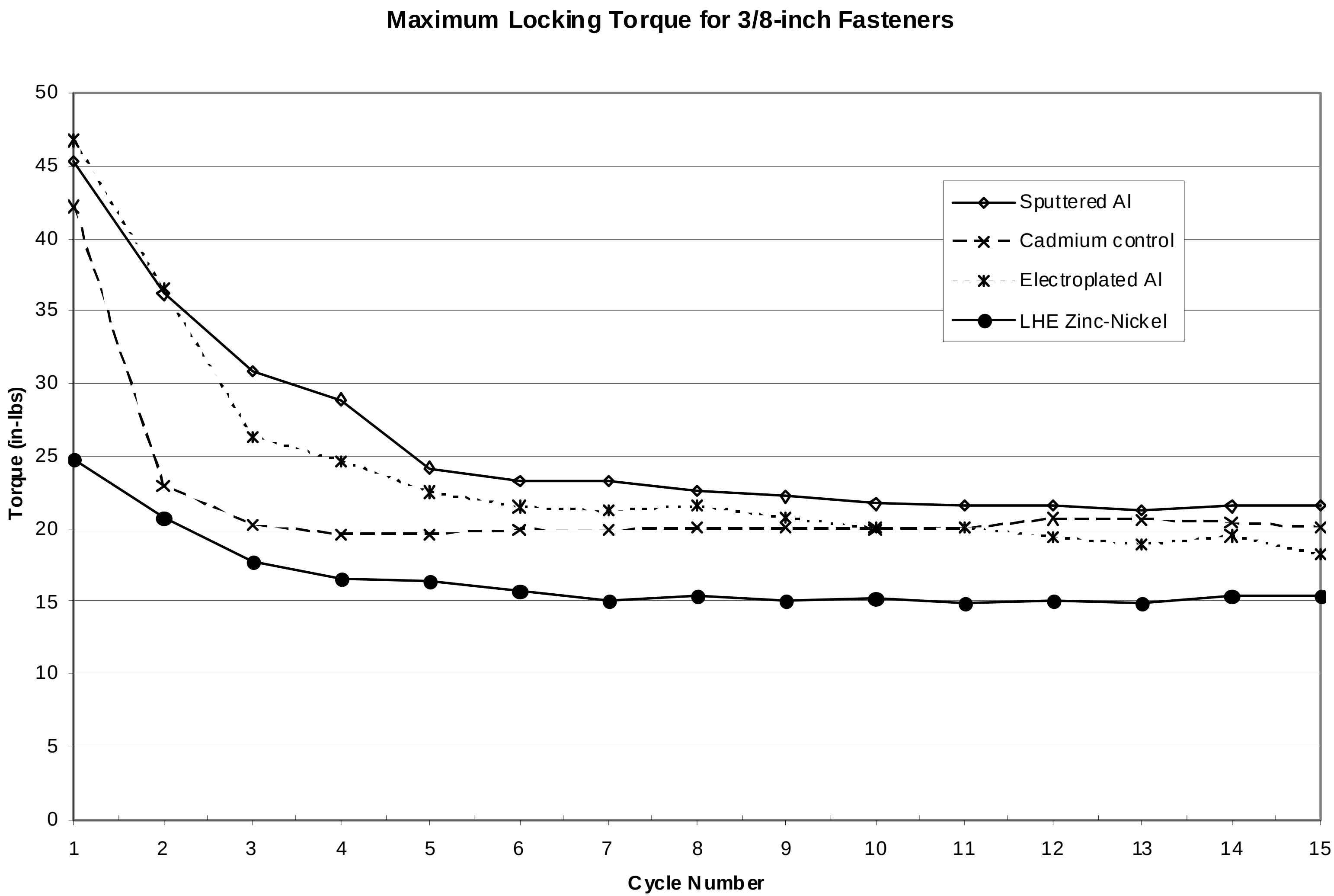
Primary / Repair Coating Hydrogen Embrittlement Quality Assurance

U.S. AIR FORCE

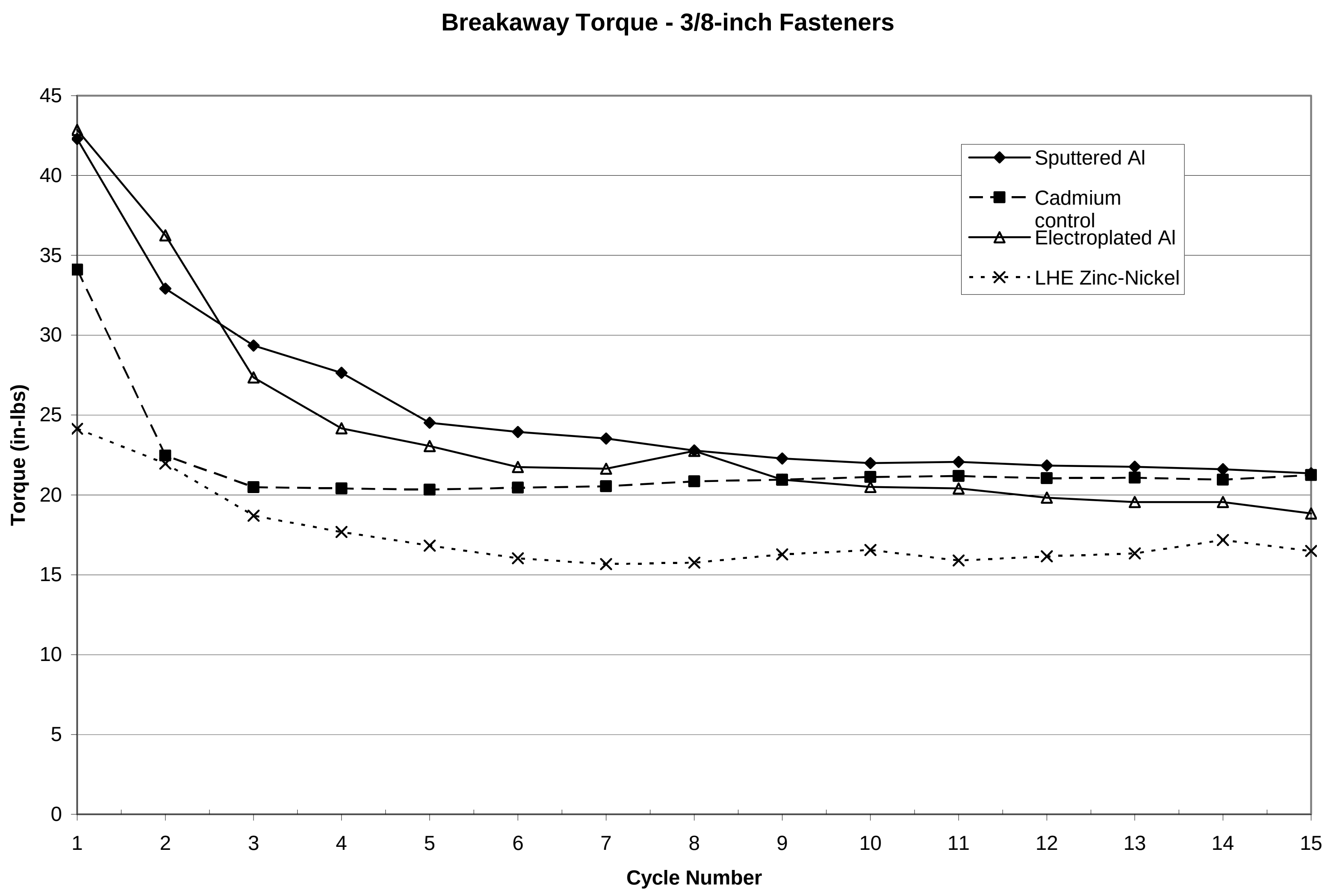
Coating	Average Fracture Strength (%)	Time to Failure (200 hour test)	Pass/Fail rating
LHE Cadmium (baseline) – Hill AFB	93.7%	204 hours	Pass
Sputtered Aluminum – Marshall Labs	97.1%	204 hours	Pass
Electroplated Aluminum – Alumiplate	97.3%	204 hours	Pass
Brush LHE Cadmium – Boeing, St. Louis	96.3%	204 hours	Pass
Brush Tin-Zinc – Boeing, St. Louis	98.1%	205 hours	Pass
Brush Zinc-Nickel – Boeing, St. Louis	93.8%	203 hours	Pass
Sermetel 249/273 – Boeing, St. Louis	96.0%	204 hours	Pass

- LHE Zn-Ni tested for hydrogen re-embrittlement only in Phase II
- IVD Al not tested for hydrogen embrittlement in Phase II

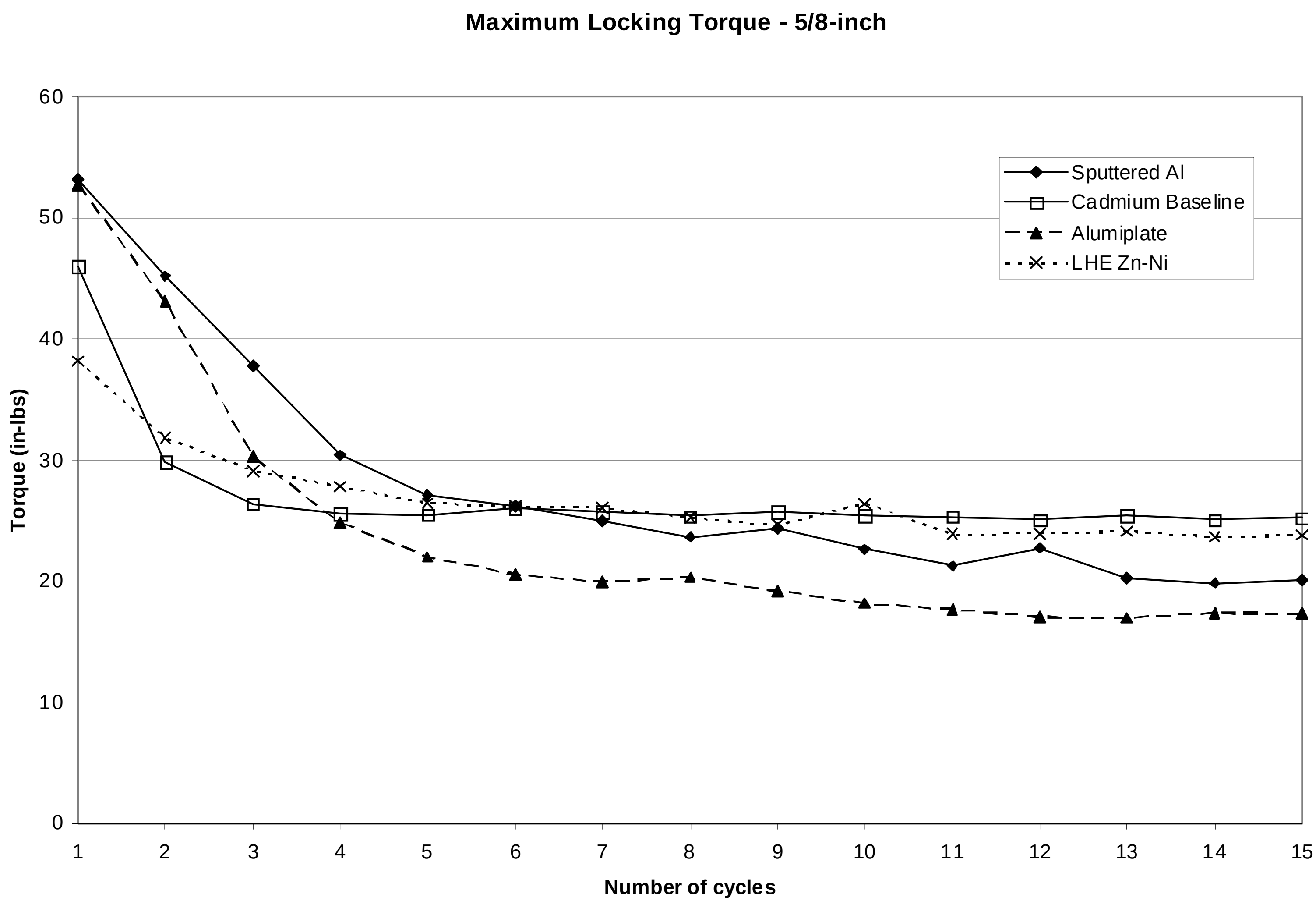
Primary Coating Run-on/Breakaway Torque Test Results



Primary Coating Run-on/Breakaway Torque Test Results



Primary Coating Run-on/Breakaway Torque Test Results



Primary Coating Run-on/Breakaway Torque Test Results